DRAFT VERSION APRIL 6, 2012
Preprint typeset using LaTeX style emulateapj v. 4/12/04

DIRECTLY IMAGING TIDALLY POWERED MIGRATING JUPITERS

SUBO DONG[1], BOAZ KATZ[2,3] AND ARISTOTLE SOCRATES[2]
Institute for Advanced Study, Princeton, NJ 08540, USA

Draft version April 6, 2012

ABSTRACT

We show that ongoing direct imaging experiments may detect a new class of long-period, highly luminous, tidally powered extrasolar gas giants. Even though they are hosted by Gyr-“old” main-sequence stars, they can be as “hot” as young Jupiters at $\sim 100\,$Myr, the prime targets of direct imaging surveys. These planets, with years-long orbits, are presently migrating to “feed” the “hot Jupiters” in steady state. Their existence is expected from a class of “high-e” migration mechanisms, in which gas giants are excited to highly eccentric orbits and then shrink their semi-major axis by factor of $\sim 10-100$ due to tidal dissipation at successive close periastron passages. The dissipated orbital energy is converted to heat, and if it is deposited deep enough into the planet atmosphere, the planet likely radiates steadily at luminosity $\sim 2-3$ orders of magnitude larger than that of our Jupiter during a typical $\sim$ Gyr migration time scale. Their large orbital separations and expected high planet-to-star flux ratios in IR make them potentially accessible to high-contrast imaging instruments on 10m-class telescopes at present and in the near future. A dozen or so such planets are expected to exist around FGK dwarfs within $\sim 50\,$pc. Long-period planets around nearby stars found by RV are viable candidates to follow up, and in particular, the highly eccentric planet HD 20782b at maximum angular separation $\sim 0.08''$ is the most promising candidate. Directly imaging these tidally powered Jupiters would enable a direct test of high-e migration mechanisms. Once detected, the luminosity would provide a direct measurement of the migration rate, and together with mass (and possibly radius) estimate, they would serve as a laboratory to study planetary spectral formation and tidal physics.

Subject headings:

1. INTRODUCTION

Jupiter and Saturn analogs orbiting other Sun-like main-sequence stars have evaded direct detection. With an effective temperature of $\sim$ 124K, an extrasolar analogue of Jupiter is fainter than a Sun-like host by $\gtrsim 10^8$ in near-IR (Kasting et al. 2009), beyond the reach of instrument capabilities at present and in the near future. While “hot Jupiters” (Jovian planets at $\lesssim 0.1\,$AU) have high temperatures and thus large planet/star flux ratios, they are too close to their hosts ($\ll 0.1''$) to be spatially resolved by 10m-class telescopes. To date, direct-imaging surveys have focused on searching for long-period massive gas giants around nearby young stars with ages $\lesssim 100\,$Myr, a strategy that has led to a number of discoveries (e.g.,Marois et al. (2008); Lagrange et al. (2010); Kalas et al. (2008)). In these systems, the planets are still “hot” – cooling down from presumably high temperatures at birth, which significantly enhances their flux ratios with host stars.

In this Letter, we discuss the possibility of directly imaging a third class of “hot” gas giants (besides close-in hot Jupiters and young Jupiters around young stars), consisting of a population of long-period, very luminous, tidally-powered planets undergoing orbital migration.

2. HIGH-ECCENTRICITY MIGRATION DUE TO TIDAL DISSIPATION

It is commonly believed that progenitors of hot Jupiters are formed with semi-major axis a at a few AU and then migrate inward to their current locations by shrinking a by factor of $\sim 10-100$. One class of proposed migration mechanisms involve exciting long-period Jupiters to highly eccentric orbits, due to gravitational interactions with stellar or planetary perturbers, enabling them to lose orbital energy at successive close periastron passages through tidal interactions with their host stars. Such “high-e” mechanisms include Kozai-Lidov Cycles plus Tidal Friction (KCTF) (Wu & Murray 2003; Fabrycky & Tremaine 2007) (see also Mazeh & Shaham (1979)), planet-planet scatter (Rasio & Ford 1996), “secular chaos” (Wu & Lithwick 2011) etc. Recently high-e mechanisms have gained observational support. A significant fraction of hot Jupiters are found to be on misaligned orbits with respect to their host stars’ spin axes (Winn et al. 2010; Triaud et al. 2010), which is a natural consequence of such mechanisms (Fabrycky & Tremaine 2007).

One general expectation from all high-e mechanisms is that there should exist a steady-state migrating population of long-period, highly eccentric gas giants “feeding” the hot Jupiters (Socrates et al. 2012). This results from the continuous generation of hot-Jupiter progenitors due to constant formation of stars and their planetary systems over the age of the Galaxy. The orbital angular momentum is approximately conserved during tidal dissipation, so the actively migrating Jupiters have $a(1-e^2) \equiv a_{\rm F}$, where $a_{\rm F} \lesssim 0.1\,$AU is the semi-major axis of their final circularized orbit. According to Socrates et al. (2012), the frequency of this population is likely an increasing function of their period (and the eccentricity), extending to that of their “source” (possibly at $\gtrsim 5\,$AU). A possible archetype of the migrating population is HD 80606b (Naef et al. 2001; Moutou et al. 2009), which is a $4M_{\rm Jup}$ planet at semi-major axis $a = 0.45\,$AU and $e = 0.93$ ($a_{\rm F} = 0.06\,$AU), accompanied by an solar-mass companion at $\sim 1200\,$AU.

Regardless of the specifics of the high-e mechanisms, a gas giant that migrates from semi-major axis a' to a over a time $\Delta t_{\rm m}$ loses orbital energy due to tidal dissipation, which is converted to heat and radiated away. This leads to an averaged

[1] Sagan Fellow
[2] John Bahcall Fellow
[3] Einstein Fellow

tidal luminosity,

$$L_m = \frac{GM_* M_p}{2\Delta t_m}\left(\frac{1}{a}-\frac{1}{a'}\right) \sim 8\times 10^{26}\,\mathrm{erg\,s^{-1}}\left(\frac{M_*}{M_\odot}\right)\left(\frac{M_p}{3M_{\rm Jup}}\right)\left(\frac{\Delta a_m^{-1}}{1\mathrm{AU}^{-1}}\right)\left(\frac{\Delta t_{\rm m}}{1\,\mathrm{Gyr}}\right)^{-1} \quad (1)$$

where M_* is the mass of the host star, M_p is the mass of the planet, $\Delta a_m^{-1} = 1/a - 1/a'$. For comparison, $L_{\rm Jup} = 8.6\times 10^{24}\,\mathrm{erg}\,s^{-1}$ is the luminosity of our Jupiter. Fabrycky & Tremaine (2007) presents a possible migration path for HD 80606b due to Kozai-Lidov Cycles plus Tidal Friction (KCTF), and in their simulation, over $\sim 0.1\,$Gyr, the "migration rate" $\Delta a_m^{-1}/\Delta t_{\rm m}$ at 0.5 AU, 1 AU, and 2 AU is $\sim$ 12, 5, and $1.4\,\mathrm{AU^{-1}\,Gyr^{-1}}$, corresponding to $L_m \sim 1.3\times 10^{28}, 5.3\times 10^{27}, 1.5\times 10^{27}\,\mathrm{erg\,s^{-1}}$, respectively, which span $\sim 1500-180\,L_{\rm Jup}$. If tidal dissipation occurs in a deep enough layer of the planet atmosphere, the thermal relaxation time $t_{\rm th}$ can be much longer than the orbital time scale ($P\sim$ yr), the planet would constantly radiate at its tidal luminosity. The upper limit of $t_{\rm th}$ is the Kevin-Helmholtz time scale, which is about 0.1 Gyr at hundreds of $L_{\rm Jup}$.

The luminosities of migrating Jupiters can be tidally enhanced by $\sim 2-3$ orders of magnitude, comparable to young Jupiters at $\sim 100\,$Myr (Burrows et al. 1997; Baraffe et al. 2003; Marley et al. 2007), which are the prime targets for ongoing and planned direct-imaging surveys (Hinkley 2011). These tidally powered Jupiters could be located at $a\sim$ several AU, and their maximum separations at apastron are further enhanced by high eccentricity $e\sim 1$ by a factor $(1+e)\simeq 2$, making them promising targets for direct-imaging detections.

Tidally powered Jupiters are not necessarily limited to those actively migrating at high eccentricity. For example, in the specific cases of KCTF, while the planet visits the highly eccentric phase that enables tidal dissipation at periastron passages in each Kozai-Lidov cycle, it typically spends much longer (factor of ~ 10 more, see Fabrycky & Tremaine (2007)) time oscillating at low-eccentricity orbits. The oscillation amplitude in e is generally larger when the planets are at longer period where relativistic precession is weaker. If the thermal time scale $t_{\rm th}$ is longer than the Kozai-Lidov time scale ($t_{\rm Kozai}\sim 0.02\,$Gyr for HD 80606b while migrating at $\sim 5\,$AU), the planet radiates approximately at the averaged tidal luminosity L_m during the whole Kozai-Lidov cycle. Therefore, the tidally-powered Jupiters include not only those at high e (i.e., small pericenter) but also a factor of ~ 10 more experiencing Kozai-Lidov oscillations at lower e.

3. DIRECT IMAGING OBSERVATIONS

The achievable sensitivity of high-contrast imaging instruments degrades substantially within the so-called inner working angle, which is often quoted to be $\sim 2-4$ times the diffraction limit, $\theta_{\rm diff}\sim\lambda/D\sim 0.02''(\lambda/1\,\mu\mathrm{m})(D/10\mathrm{m})^{-1}$, where λ is the observed wavelength and D is telescope aperture. Several high-contrast imaging instruments are and will be commissioned in the near future on a number of 5-10m telescopes, such as Gemini GPI (Macintosh et al. 2008), VLT SPHERE (Beuzit et al. 2008), Subaru HiCHAO (Martinache & Guyon 2009), LBTI (Hinz et al. 2008), and Palomar Project 1640 (Hinkley et al. 2011), etc. The best contrast goals of these instruments are $10^{-7}-10^{-8}$ in near-IR beyond the inner working angle (Hinkley 2011).

At a migration rate of $\Delta a_m^{-1}/\Delta t_{\rm m} = 1-10\,\mathrm{AU^{-1}\,Gyr^{-1}}$, tidal luminosities for $\sim 3M_{\rm Jup}$ planets are $\sim 2\times 10^{-7}-2\times 10^{-6}L_\odot$ ($\sim 10^2$ - $10^3 L_{\rm Jup}$), corresponding to blackbody effective temperatures $T_{\rm eff}\sim 390K-690K$ for a planet radius $1R_{Jup}$. The peaks of the black body radiation at these temperatures are at $\sim 9-5\,\mu$m. The black body contrast ratios at $3.6\,\mu$m (L-band) of the planet to a Sun-like star ($T_{\rm eff}\sim 5800K$) are $\sim 3\times 10^{-7}-3\times 10^{-5}$. At bands further away from the peak (e.g., $\sim 1\,\mu$m), black body radiation is exponentially suppressed, resulting in very low flux ratios. However, the near-IR spectral energy distribution is unlikely to be well described by black body emission. For example, Jupiter has a spectral window allowing for probing deeper, warmer layers of the atmosphere that leads to orders of magnitude larger flux than that of a 125K blackbody in near-IR (Kasting et al. 2009). We note that according to Burrows et al. (1997)'s model, at effective temperatures $400K$ and $600K$, with surface gravity $10^4\mathrm{cm\,s^{-2}}$, the contrast ratios in [H, L]-band with a Sun-like star are approximately $[4\times 10^{-7}, 4\times 10^{-6}]$, $[4\times 10^{-6}, 2.5\times 10^{-5}]$, respectively.

Socrates et al. (2012) estimate that the frequency of long-period (hundreds of days), highly-eccentric Jupiters is about 10% that of hot Jupiters, whose occurrence rate is estimated to be $\sim 1\%$ around FGK dwarfs (Marcy et al. 2005). Therefore, $\sim 0.1\%$ of solar-type stars may host this population. There are $\sim 10^4$ FGK dwarfs within $\sim 50\,$pc of the Sun, which amounts to ~ 10 potentially tidally-powered Jupiters.

Rather than doing a blind search as employed in current direct-imaging surveys, one strategy to identify these tidally-powered Jupiters is to follow up long-period, highly eccentric planets with known radial velocity (RV) orbits, which are likely to be actively migrating. For $e\sim 1$, one obtains maximum projected separation very close to apastron at $r_{\perp,\rm max}\approx 2a\sqrt{\sin^2\omega\cos^2 i+\cos^2\omega}$, where ω is the argument of periastron. There is one RV planet, with $a\sim 1\,$AU and $a_{\rm F}\lesssim 0.1\,$AU, known as HD 20782b (Jones et al. 2006; O'Toole et al. 2009) at 36 pc, and the best-fit parameters are $M\sin i = 1.9M_{\rm Jup}$, $a = 1.38\,$AU, $e = 0.97$, $\omega = 148^o$ (note that the eccentricity needs to confirmed as the periastron passage was not sufficiently probed). It reaches maximum angular separation at $(0.28\cos^2 i+0.72)0.076''$ at apocenter, which corresponds to $\lesssim 3\lambda/D$ at H-band and $\sim\lambda/D$ at L-band for a 10m telescope and more favorable for LBTI (22.8m baseline) in terms of spatial resolution.

As previously discussed, if KCTF takes place, many long-period, low-e Jupiters can be tidally-powered by radiating heat accumulated from past high-e visits, and their occurrence rate can be ~ 10 larger than that of the actively-migrating, high-e population. A possible observation strategy would be to directly image all RV planets with sufficiently large maximum angular separations and probe this population (as well as those that show a linear trend, which indicates the probable presence of long-period planets). Planetary systems with known perturbers from RV residuals or imaging may receive preference since the planets in these system have a higher probability of Kozai-Lidov oscillation. It may also be possible to remove the speckle noise more efficiently and improve the detection sensitivity with information from the known orbital phase from RV, which will further boost the detectable contrast ratio and obtain smaller inner working angle. Since a large fraction of nearby main-sequence stars have not been monitored by RV sufficiently long to find long-period Jupiters, a more ambitious strategy would be to do a blind search of all FGK stars in the solar neighborhood.

4. DISCUSSION AND FUTURE PROSPECT

If the tidally-powered Jupiters are directly imaged, their luminosities provide a direct measure of planet migration rate due to tidal dissipation and thus constrain high-e migration mechanisms. Note however thermal tidal power generated at pericenter passages could be responsible for tidally powering long-period Jupiters Arras & Socrates (2009a,b, 2010). In that case, the source of energy is from star light rather than orbit. Combined with RV orbits, one can break the inclination degeneracy in RV to obtain the de-projected true mass and full orbital solution, making them an excellent laboratory to study planetary dynamics. With measured mass and luminosity, one may probe the spectral formation of gas giant atmosphere as well as the physics of tidal dissipation. It is interesting to note that, even though similar high-e population may exist for binary stars (Dong et al. 2012), it is much more difficult to measure tidal luminosity directly due to nuclear burning.

As discussed in Socrates et al. (2012) and Dawson & Johnson (2012), transit surveys such as *Kepler* are ideal to find the eccentric migrating Jupiters due to their enhanced transit probability. Space-based transit surveys that target bright stars such as TESS (Ricker et al. 2009) and PLATO (Catala et al. 2011) will potentially provide an excellent sample of tidally-powered planets hosted by nearby stars that are suitable for direct-imaging study. For transiting planets, high-precision IR light curves with secondary eclipse could in principle directly measure the tidal luminosity for these planets as well (see Laughlin et al. (2009)).

Ground-based high-contrast imaging instruments are experiencing rapid development over the last few years, and the tidally powered Jupiters may turn out to be the most luminous planets to image for nearby solar-type main-sequence stars. New instruments such as GPI, HiCHAO, LBTI etc should already be able to probe this population. Future telescopes such as TMT, GMT and ELT can conduct a thorough survey for this population around nearby stars due to their smaller diffraction limits. Space-based missions such as JWST, TPF, and DARWIN will potentially be able to make detailed spectroscopic studies.

We thank Andy Gould, Cullen Blake, Jose Prieto, Scott Tremaine, Matias Zaldarriaga, Dave Spiegel and Rashid Sunyaev for discussions. Work by SD was performed under contract with the California Institute of Technology (Caltech) funded by NASA through the Sagan Fellowship Program. BK is supported by NASA through the Einstein Postdoctoral Fellowship awarded by Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060. AS acknowledges support from a John N. Bahcall Fellowship awarded at the Institute for Advanced Study, Princeton.

REFERENCES

Arras, P., & Socrates, A. 2009, arXiv:0912.2318
Arras, P., & Socrates, A. 2009, arXiv:0901.0735
Arras, P., & Socrates, A. 2010, ApJ, 714, 1
Baraffe, I., et al. 2003, A&A, 402, 701
Beuzit, J.-L., Feldt, M., Dohlen, K., et al. 2008, Proc. SPIE, 7014,
Burrows, A., et al. 1997, ApJ, 491, 856
Catala, C., Appourchaux, T., & Plato Mission Consortium 2011, Journal of Physics Conference Series, 271, 012084
Dawson, R. I., & Johnson, J. A. 2012, arXiv:1203.5537
Dong, S., Katz, B., & Socrates, A. 2012, arXiv:1201.4399
Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298
Hinkley, S., Oppenheimer, B. R., Zimmerman, N., et al. 2011, PASP, 123, 74
Hinkley, S. 2011, arXiv:1112.1765
Hinz, P. M., Solheid, E., Durney, O., & Hoffmann, W. F. 2008, Proc. SPIE, 7013,
Jones, H. R. A., Butler, R. P., Tinney, C. G., et al. 2006, MNRAS, 369, 249
Kalas, P., Graham, J. R., Chiang, E., et al. 2008, Science, 322, 1345
Kasting, J., Traub, W., Roberge, A., et al. 2009, astro2010: The Astronomy and Astrophysics Decadal Survey, 2010, 151
Lagrange, A.-M., Bonnefoy, M., Chauvin, G., et al. 2010, Science, 329, 57
Laughlin, G., Deming, D., Langton, J., et al. 2009, Nature, 457, 562
Macintosh, B. A., Graham, J. R., Palmer, D. W., et al. 2008, Proc. SPIE, 7015,
Marcy, G., Butler, R. P., Fischer, D., et al. 2005, Progress of Theoretical Physics Supplement, 158, 24
Marley, et al. 2007, ApJ, 655, 541
Marois, C., Macintosh, B., Barman, T., et al. 2008, Science, 322, 1348
Martinache, F., & Guyon, O. 2009, Proc. SPIE, 7440,
Mazeh, T., & Shaham, J. 1979, A&A, 77, 145
Moutou, C., Hébrard, G., Bouchy, F., et al. 2009, A&A, 498, L5
Naef, D., Latham, D. W., Mayor, M., et al. 2001, A&A, 375, L27
Rasio, F. A., & Ford, E. B. 1996, Science, 274, 954
Ricker, G. R., Latham, D. W., Vanderspek, R. K., et al. 2009, Bulletin of the American Astronomical Society, 41, #403.01
Showman, A. P., Fortney, J. J., Lian, Y., et al. 2009, ApJ, 699, 564
Socrates, A., Katz, B., Dong, S., & Tremaine, S. 2012, ApJ, in press, arXiv:1110.1644
O'Toole, S. J., Tinney, C. G., Jones, H. R. A., et al. 2009, MNRAS, 392, 641
Triaud, A. H. M. J., Collier Cameron, A., Queloz, D., et al. 2010, A&A, 524, A25
Winn, J. N., Fabrycky, D., Albrecht, S., & Johnson, J. A. 2010, ApJ, 718, L145
Wu, Y., & Murray, N. 2003, ApJ, 589, 605
Wu, Y., & Lithwick, Y. 2011, ApJ, 735, 109